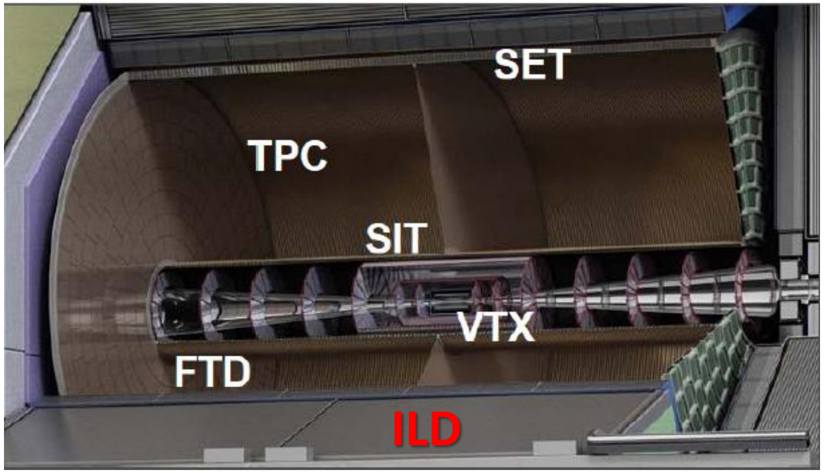
Interplay beam pipe, background and vertex detectors:
Concerns on Beam Related Background Governing the Design of Tracking Devices

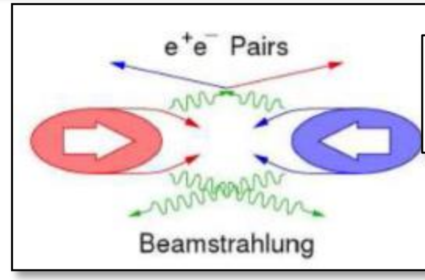
Marc Winter (IJCLAB - Orsay) & Auguste Besson (IPHC – Strasbourg)

- Impact of BS on technological choices of tracking sub-systems
- Questions on predictions
- Questions on beam optics and BS enveloppe
- Questions on BG besides BS
- Questions on beam pipe



Reminder: Impact of BS on technological choices

- Beam related BG dominates the hit rate of vertex detector as well as inner and end-cap trackers
  - ✓ It governs their read-out architectures & technological choices
  - ✓ Percent level occupancy is considered as acceptable: ~few BX resolution time needed (0.5 – 4 μs)



$$\sigma_b < 5 \oplus \frac{10}{p\beta \sin^{\frac{3}{2}}\theta}\ \mu m$$

Time resolution
O(0.5-4 μs)

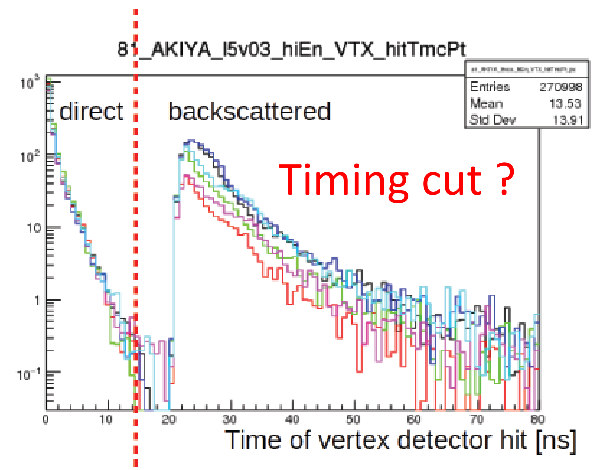
ILD @ 250 GeV

ILD_l5_v05	hits/BX			hits/BX/cm²		
	mean	±	RMS	mean	±	RMS
VXD 1	914	±	364	6.64	±	2.65
VXD 2	545	±	207	3.96	±	1.51
VXD 3	129	±	60	0.213	±	0.100
VXD 4	107	±	53	0.177	±	0.088
VXD 5	40	±	26	0.043	±	0.029
VXD 6	34	±	24	0.037	±	0.026

Daniel Jeans, Akiya Miyamoto

- For the vertex detector, it narrows down the sensor technological choice (presently) to CMOS pixel sensors, excluding for instance FPCCDs, which are more precise but not adapted to the hit rate:
  - ✓ ~ 3 μm (CMOS) against 1 μm (FPCCD)

- Even in the case of CMOS pixel sensors, a trade-off is to be found to accommodate the hit rate, based on an interplay between pixel pitch, read-out speed and power consumption
  - ✓ achieving simultaneously the ambitioned spatial resolution & material budget is an issue
    - Targeted Mat.Budget ~0.15% X_0 / layer

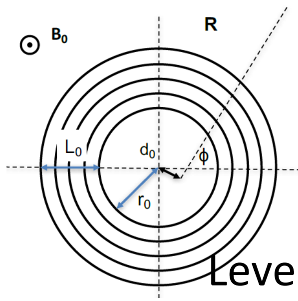


Cut at 15 ns

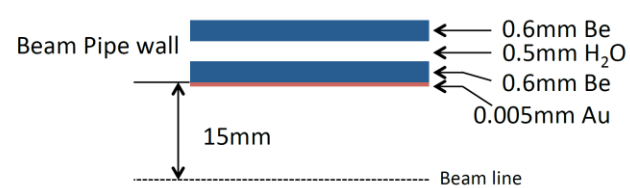
Quest for updates

- **Relevant sources of beam related backgrounds:**
  - ✓ news on beamstrahlung since TDR ? (D.Jeans/A.Miyamoto studies)
  - ✓ other phenomena: synchrotron radiation, infra-red radiation, ...
  - ✓ are there potential transitory backgrounds ?
  - ✓ consequences of potential luminosity upgrade (change in optics ?)
- **Which are the suspected sources of uncertainty** on the prediction of beam related backgrounds:
  - ✓ beamstrahlung generators: γ & $e^{\pm}$ rates, momentum spectrum
  - ✓ other phenomena: synchrotron radiation, infra-red radiation, ...
  - ✓ corresponding safety factors ? x3-5 ?
- **Beam parametres:**
  - ✓ beamstrahlung envelope at small polar angle prevents reconstruction of shallow tracks close to IP
  - ✓ at SuperKEKb (and FCCee < Sync. radiation) beam pipe cooling is considered as mandatory: Why not at ILC ?
    - Cooling ⇨ beam pipe material budget x 2 (~0.15%X_0 ⇨ 0.3%X_0)
  - ✓ At FCCee they consider reducing the inner radius (more material budget, lower magnetic field w.r.t. ILC)
    - Is it worth considering it ?

$$\Delta d_0|_{res.} \approx \frac{3\sigma_{r\phi}}{\sqrt{N+5}}\sqrt{1+\frac{8r_0}{L_0}+\frac{28r_0^2}{L_0^2}+\frac{40r_0^3}{L_0^3}+\frac{20r_0^4}{L_0^4}}$$

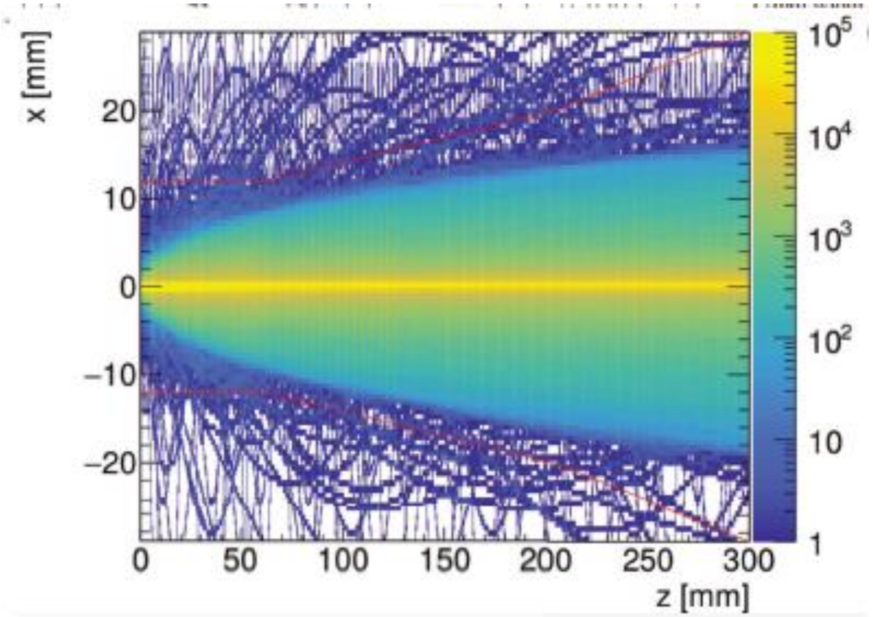


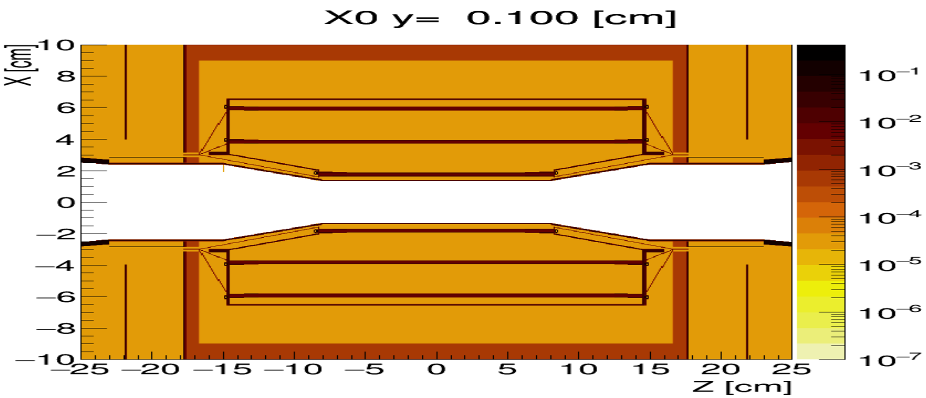
Level arm !



FCCee beampipe

Beam background enveloppe

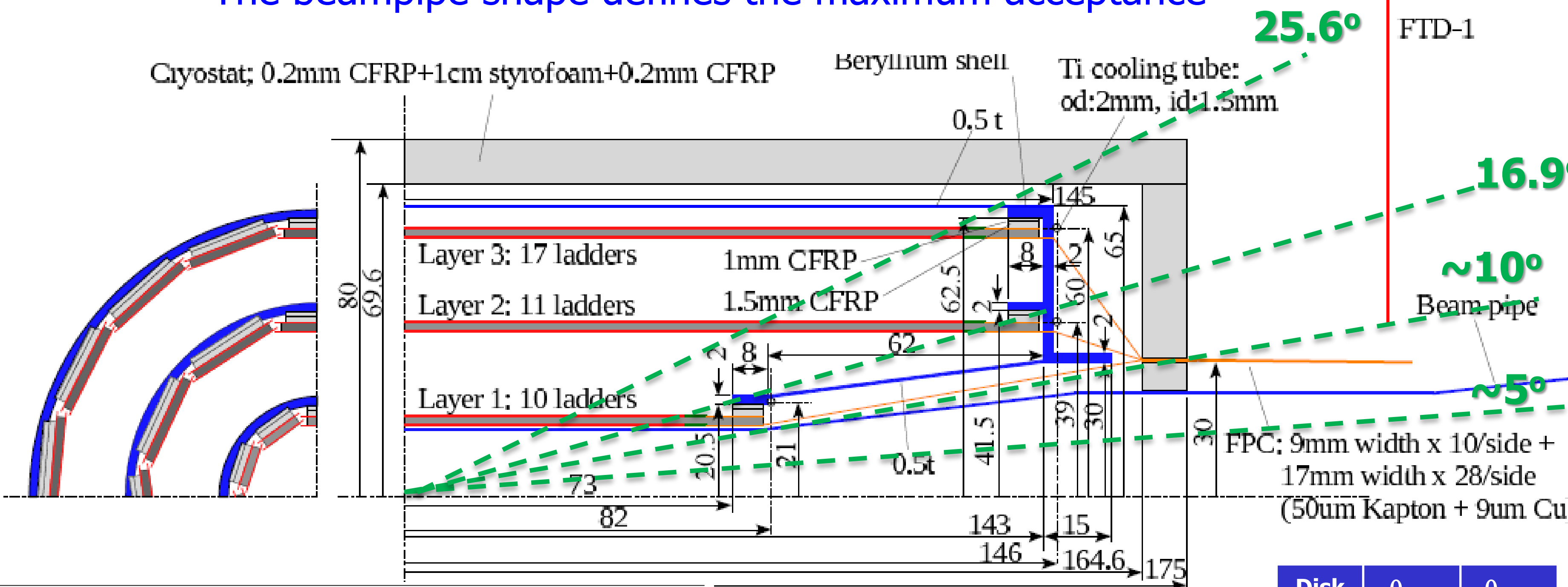




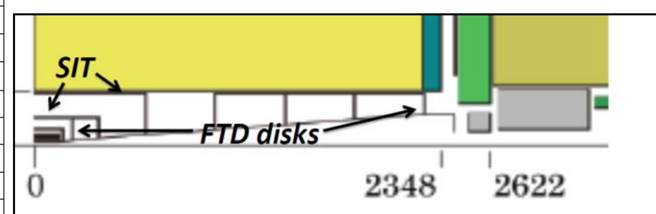
The beam background enveloppe defines somehow the acceptance limit

Geometry in the forward region (ILD)

The beampipe shape defines the maximum acceptance



FTD characteristics (design baseline: pixels for two inner disks, microstrips for the rest))				
Geometry			Characteristics	Material
R[mm]	Z[mm]	cosθ	Resolution R-ϕ[μm]	RL[%]
39-164	220	0.985-0.802	σ=3-6	0.25-0.5
49.6-164	371.3	0.991-0.914		0.25-0.5
70.1-308	644.9	0.994-0.902	σ=7.0	0.65
100.3-309	1046.1	0.994-0.959		0.65
130.4-309	1447.3	0.995-0.998		0.65
160.5-309	1848.5	0.996-0.986		0.65
190.5-309	2250	0.996-0.990		0.65

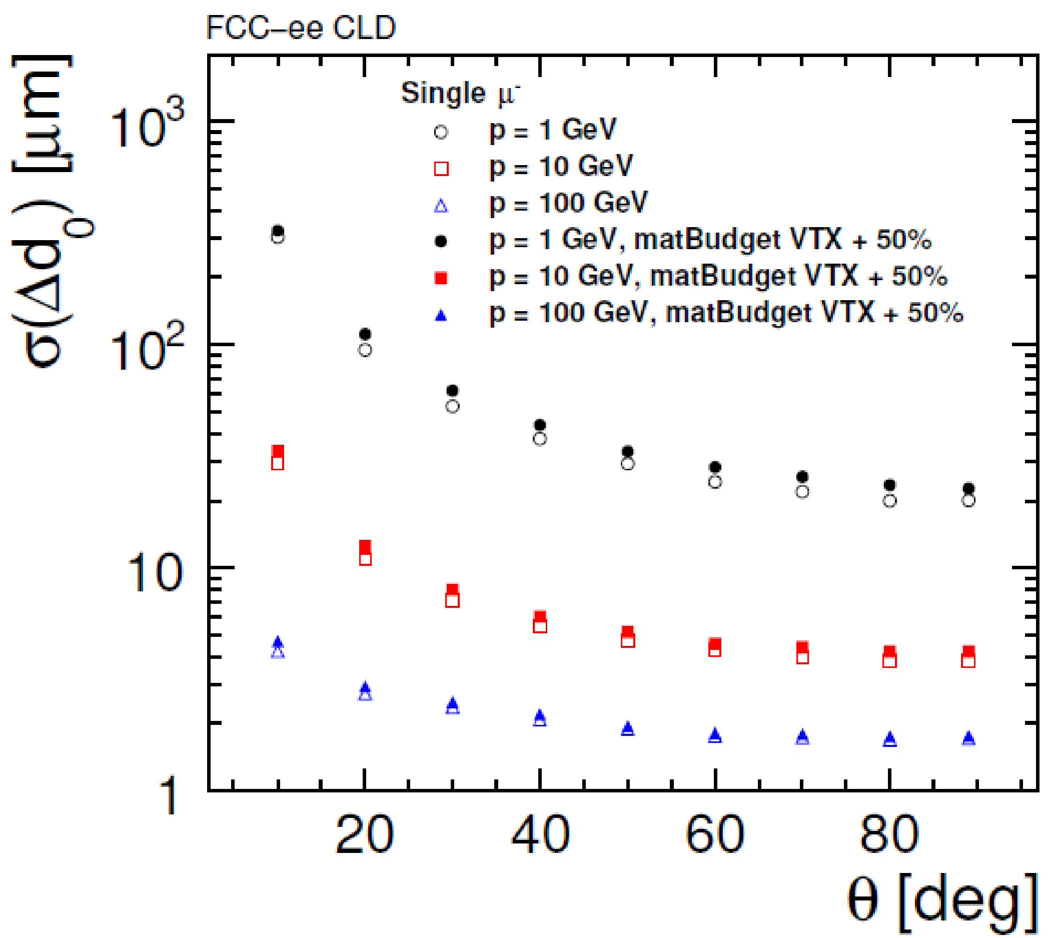


Disk	θ_{min}	θ_{max}
1	10.1°	36.7°
2	7.6°	23.8°
3	6.2°	25.5°
4	5.5°	16.5°
5	5.1°	12.1°
6	5.0°	9.5°
7	4.8°	7.8°

Polar θ (°)	>25.5	25.5-17	17-10	10-5
VXD hits	6	4	0	0
FTD hits (disks)	0	2-3 (1-2-3)	4 (1-2-3-4)	4-6 (2 to 7)

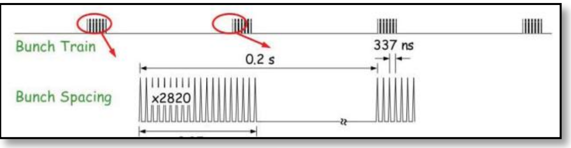
Back up

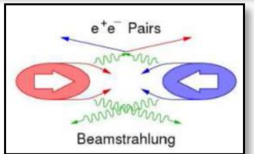
Material budget: FCCee example



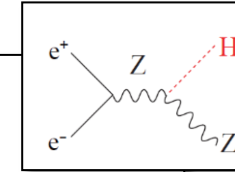
(a) d_0 resolution

ILC/FCCee Vertex detector requirements





Physics
⇨ Flavour tagging
⇨ Low pT tracks
⇨ Vertex/Jet charge determination



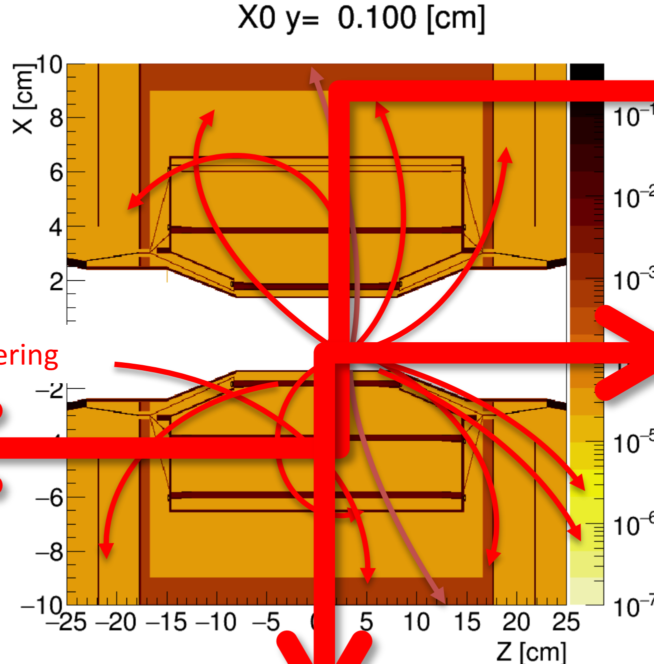
Physics (<Hz/cm²)

Beam background (~ 5 hits/BX/cm² on layer 0, ILC)

Beam background

Radiation hardness
O(100kRad/yr) & O(10^{11})n_{eq}/yr

Rad.Tol. devices



Back scattering

Vertex reconstruction
⇨ granularity
⇨ Pitch ~17 um
⇨ (σ_{sp} ~3 um)

Material Budget
⇨ ~ 0.15% X_0 / layer
⇨ < 1% X_0 for the whole VTX
~ 900 μm Si
+ ~0.14% X_0 for the beam pipe (ILC)
+ ~0.3 % X_0 for the beam pipe (FCC)

Read-out speed
O(1-10 μs)

Power consumption
~< 50mW/cm²

Low material detectors & supports structures

Fast read-out & low Power Architectures (~ 20 mW/cm²)

Cooling
Stiffness / Alignment

$$\sigma_{d_0} = a \oplus \frac{b}{p \sin^{3/2}\theta}$$

$a \simeq 5\,\mu m$; $b \sim 15\,\mu m.GeV$ FCCee

$b \sim 10\,\mu m.GeV$ ILC

Power pulsing (ILC) vs continuous beam (FCCee)

Challenge:

⇨Keep excellent spatial resolution, low material budget, moderate Power consumption and push towards better time resolution (BX)

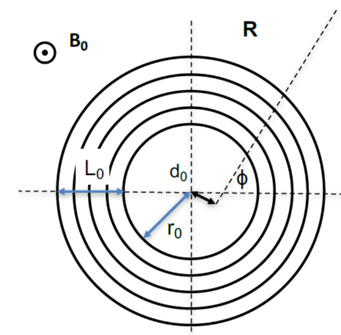
Spatial resolution in Higgs factories

- Why do we need vertexing and tracking ?
  - ✓ Reconstruct Primary and secondary vertex
    - Heavy flavor tagging (b, c, τ)
    - Order of magnitude: O(1μm) – O(10μm)
  - ✓ Low momentum tracking
    - pT ~< 100 MeV/c – 1 GeV/c
  - ✓ Vertex/Jet charge determination

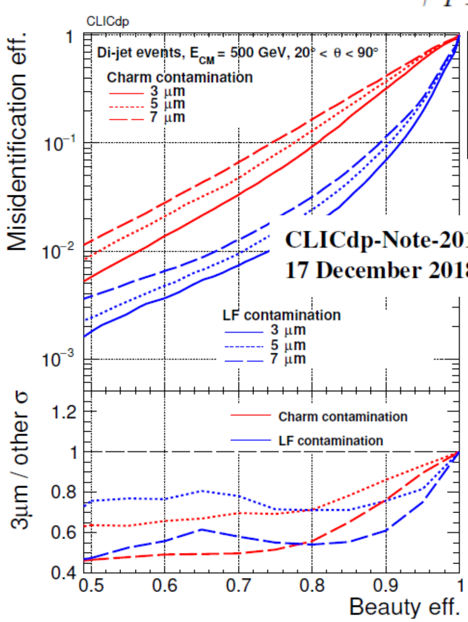
$$\sigma_{d0}{}^2 = a^2 + \left(\frac{b}{p.\sin^{3/2}\theta}\right)^2$$

$$\Delta d_0|_{res.} \approx \frac{3\sigma_{r\phi}}{\sqrt{N+5}}\sqrt{1+\frac{8r_0}{L_0}+\frac{28r_0^2}{L_0^2}+\frac{40r_0^3}{L_0^3}+\frac{20r_0^4}{L_0^4}}$$

$$\Delta d_0|_{m.s.} \approx \frac{0.0136\,\mathrm{GeV/c}}{\beta p_T} r_0 \sqrt{\frac{d}{X_0\sin\theta}}\sqrt{1+\frac{1}{2}\left(\frac{r_0}{L_0}\right)+\frac{N}{4}\left(\frac{r_0}{L_0}\right)^2}$$

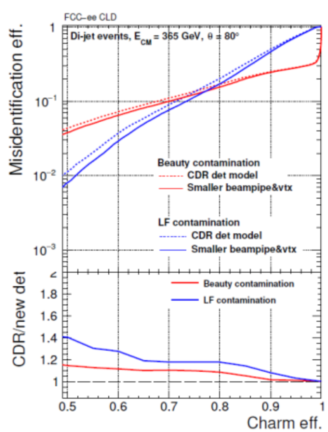


Level arm !



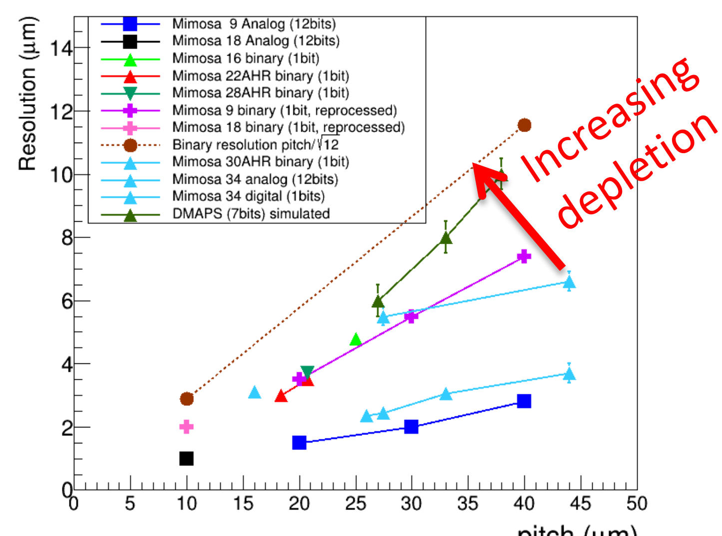
CLICdp-Note-2018-00
17 December 2018

Sensitivity to b/c-tagging performances



LCD-Note-2019-001
25 November 2019

CMOS pixel resolution vs pitch



⇨ σ_{sp} ~ 3 μm ⇦⇨ pitch ~ 17 μm
(assuming binary output, ~20 μm epi.thickness & partial depletion in 180nm tech.)

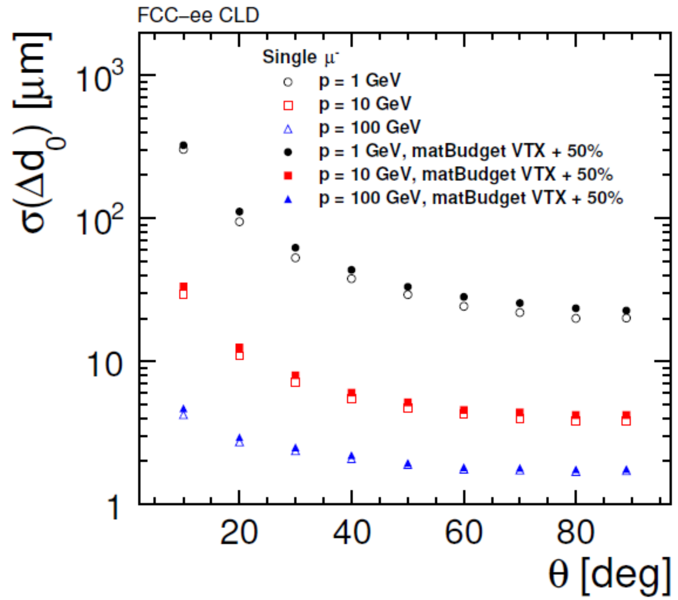
Material budget in Higgs factories

$$\sigma_{d0}{}^2 = a^2 + \left(\frac{b}{p.\sin^{3/2}\theta}\right)^2$$

- Driving parameter
  - ✓ Inner radius

$$\Delta d_0|_{m.s.} \approx \frac{0.0136\,\mathrm{GeV/c}}{\beta p_T} r_0 \sqrt{\frac{d}{X_0 \sin\theta}} \sqrt{1 + \frac{1}{2}\left(\frac{r_0}{L_0}\right) + \frac{N}{4}\left(\frac{r_0}{L_0}\right)^2}$$

  - ✓ Beam pipe
    - Constant term ~ 0.15-0.3 % X_0
  - ✓ Material budget / layer
    - Requirement ~ ~0.15% X_0 /layer



(a) d_0 resolution

Sensitivity to impact parameter resolution

- Material budget optimization
  - ✓ Double sided approach
    - PLUME prototypes
  - ✓ Stitching (see later)
    - Larger surfaces
  - ✓ Bent sensors (see later)
    - Optimize
  - ✓ Integration
    - Cooling system, mech. Support, cabling, Powering scheme, etc.

Power & cooling in Higgs Factories

- Baseline:
  - ✓ air flow cooling only to minimize material budget
  - ✓ Up to ~ 20 mW/cm^2
- Driving parameters:
  - ✓ # channels, Time resolution / data flux
  - ✓ Surface (VXD ~ 3500 cm^2)
- Power Pulsing (ILC/CLIC)
  - ✓ Constraints more relaxed w.r.t. FCCee

Power Analog ($mW/chip$)	49.22
Power Bias ($mW/chip$)	4.5
Power PriorityEncoder ($mW/chip$)	4.219
Power DigitalPeriphery ($mW/chip$)	64.27
Power PLL ($mW/chip$)	18.5
Power Serializer With Data ($mW/chip$)	86.06
Power Serializer With No Data ($mW/chip$)	0
Power LVDS ($mW/chip$)	56.4

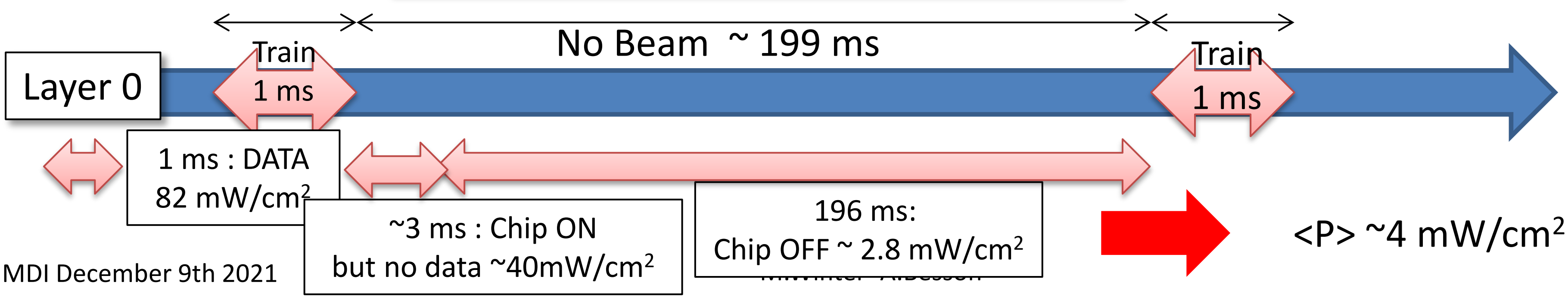
MIMOSIS like architecture, 180 nm

Period	Relative Energy
E during train	225 mJ ~ 4 %
E between train (Power ON)	380 mJ ~ 6 %
E between train (Power OFF)	5740 mJ ~ 90 %

Beam background rate	Read-out speed	<Power (NO P.P.)	<Power> (P.P.)	
	(µs)	(W)	Conservative	Ambitious
DBD	4 µs	102 W (~30mW/cm^2)	~31 W (~10 mW/cm^2)	~12 W
DBD	2 µs	122 W (~33mW/cm^2)		
DBD x 2	4 µs	107 W		
DBD x 2	2 µs	127 W		

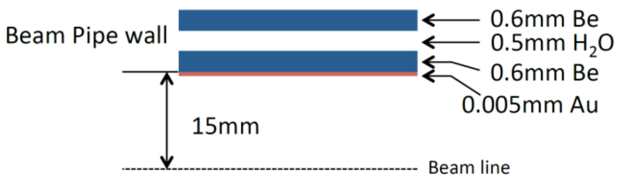
Layers	Relative Power
Layers 0/1	~ 10 %
Layers 2/3	~ 35%
Layers 4/5	~ 55 %

Challenge: Air flow cooling only



ILC & FCC differences

- Beam structure: « continuous » vs trains
  - ✓ Power Pulsing: allows a factor O(10) reduction in average power
  - ✓ ILC: However, avoiding PP is desirable (alignment)
- Beam pipe shape and material
  - ✓ ILC: ~0.14% X_0 for the beam pipe (500 μm)
  - ✓ FCCee: Sync. Radiations ⇨ Cooling of the beam pipe ⇨ higher Mat.Budget
  - ⇨ 800 (2 pipes) + 400 (water) ~ 1200 um Be eq.)
  - ⇨ Smaller inner radius @ FCCee ?



- MDI:
  - ✓ CLD: Forward acceptance limited to 150 mradian (8.6°)
  - ✓ ILD: Froward acceptance (disks) ~ 5°
- TeraZ vs Giga Z
  - ✓ Specific timing and impact parameter resolution ?
    - e.g. lower radius ?
- Magnetic field:
  - ✓ ILC: 3.5/4 T (R_{max} ~1.8m)
  - ✓ CLIC: R_{max}(CLIC): 1.5m
  - ✓ FCC: 2 T max ⇨ compensate by larger level arm (R_{max} ~ 2.15m)

e^+e^- collider beam parameters

Linear

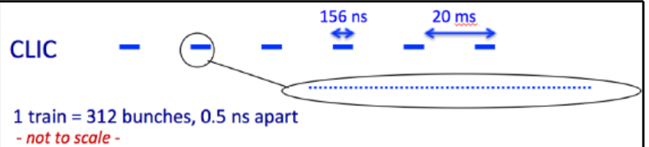
Parameter	ILC 250 GeV	ILC 500 GeV	CLIC 380 GeV	CLIC 1.5 TeV	CLIC 3 TeV
Luminosity L ($10^{34}cm^{-2}sec^{-1}$)	**1.35**	**1.8**	**1.5**	**3.7**	**5.9**
L > 99% of √s ($10^{34}cm^{-2}sec^{-1}$)	1.0	1.0	0.9	1.4	2.0
Repetition frequency (Hz)	5	5	50	50	50
Bunch separation (ns)	554	554	0.5	0.5	0.5
Number of bunches per train	1312	1312	352	312	312
Beam size at IP σ_x/σ_y (nm)	515/7.7	474/5.9	150/2.9	~60/1.5	~40/1
Beam size at IP σ_z (μm)	300	300	70	44	44

ILC: Crossing angle 14 mrad, e^- polarization ±80%, e^+ polarization ±30%
CLIC: Crossing angle 20 mrad, e^- polarization ±80%

Very small beams + high energy => beamstrahlung

Very small bunch separation at CLIC drives timing requirements for detector

Very low duty cycle at ILC/CLIC allows for:
Triggerless readout
Power pulsing



Circular

	FCC-ee Z	FCC-ee Higgs	FCC-ee ttbar	CEPC Z (2T)	CEPC Higgs
√s [GeV]	**91.2**	**240**	**365**	**91.2**	**240**
Luminosity / IP ($10^{34}cm^{-2}s^{-1}$)	**230**	**8.5**	**1.7**	**32**	**1.5**
no. of bunches / beam	16640	393	48	12000	242
Bunch separation (ns)	**20**	994	3000	**25**	680
Beam size at IP σ_x/σ_y (μm/nm)	6.4/28	14/36	38/68	6.0/40	20.9/60
Bunch length (SR/BS) (mm) / Beam size at IP σ_z (mm)	3.5/12.1	3.3/5.3	2.0/2.5	8.5	4.4

Beam transverse polarisation
=> beam energy can be measured to very high accuracy (~50 keV)

At Z-peak, very high luminosities and **very high e^+e^- cross section (40 nb)**
⇒ **Statistical accuracies at 10^{-4} -10^{-5} level ⇒ drives detector performance requirements**
⇒ **Small systematic errors required** to match
⇒ This also drives requirement on **data rates** (physics rates 100 kHz)
⇒ Triggerless readout likely still possible

Beam-induced background, from beamstrahlung + synchrotron radiation
- Most significant at 365 GeV
- Mitigated through MDI design and detector design

Modified from Lucie Linssen, ESPPU, 2019

Mogens Dam / NBI Copenhagen AIDA++ Open Meeting, CERN 4 September, 2019 6

(slide from Mogens Dam/Lucie Linssen)